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BLUE LOOPS DURING CORE HELIUM BURNING AS THE CONSEQUENCE OF MODERATE CONVECTIVE ENVELOPE OVERSHOOTING IN STARS OF INTERMEDIATE TO HIGH MASS

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ABSTRACT

New calculations of stellar evolutionary sequences without semiconvection in any phase have unexpectedly turned up, for stars in the mass range 3–30 $M_{\odot}$, an irregular pattern of blue loops on the H-R diagram during the core helium-burning phase. Blue loops occur for 3 and 10 $M_{\odot}$, but not for 5, 7, 15, and 30 $M_{\odot}$. It is found, however, that the models near the bottom of the red supergiant branch are only marginally stable against small inward displacements of the former base of the outer convection zone when it was deepest, for the stellar mass range 5–15 $M_{\odot}$. As a consequence, convective envelope overshooting need only penetrate a distance of ~ 0.3 of a local pressure scale height to promote a delayed blue loop in these particular sequences. In conformity with previous work, the triggering mechanism for the blue loop appears to be proximity of the hydrogen-burning shell to the hydrogen discontinuity at the former base of the outer convection zone.

Subject headings: stars: evolution — stars: interiors — stars: supergiants

1. INTRODUCTION

Blue loops that emerge from the region of red supergiants on the H-R diagram during the core helium-burning phase are still rather hard to pin down, especially in stellar models of intermediate and high mass. Variations in physical input parameters that favor the occurrence of blue loops have long been identified, but the actual trigger in many cases seems to be the relative proximity of the hydrogen-burning shell to the hydrogen discontinuity that marks the former base of the homogeneous outer convective envelope when it was deepest (Lauterborn, Refsdal, & Roth 1971; Robertson 1972; Stothers & Chin 1973; Schlesinger 1977).

Since a blue loop is apparently promoted by a more nearly perfect rectangular profile of the hydrogen mass distribution in the envelope, deep convective overshooting by the outer convection zone may be able to trigger a blue loop that otherwise would not occur. Numerical experiments on evolving stellar models of 30 $M_{\odot}$ have already demonstrated that a sufficiently deep inward convective penetration at the stage when the convective envelope is normally deepest (at the top of the red supergiant branch) can artificially trigger a prompt blue loop (Stothers & Chin 1981).

What seems to be not widely recognized, however, is the rather marginal state of stability naturally existing in many stellar models near the bottom of the red supergiant branch during the phase of core helium depletion. Numerical tests for secular instability in the usual linear approximation of perturbation theory do not always indicate such a condition (Noels & Gabriel 1973; Gabriel, Refsdal, & Ritter 1974; Gabriel & Noels 1974) because a secularly stable model appears perfectly stable, even though a small change in its structure could make it unstable. In a few isolated cases where two computer runs of ostensibly the same evolutionary track, but with different criteria for numerical accuracy, yielded a blue loop for one run and no blue loop for the other, an exactly marginal state of stability was apparently present (9 $M_{\odot}$, Fricke, Stobie, & Strittmatter 1971; Meyer-Hofmeister 1972; 15 $M_{\odot}$, Paczyński 1970b; 30 $M_{\odot}$, Stothers & Chin 1975).

In this paper, we establish more fully: (1) the generality of this type of marginal stability near the bottom of the red supergiant branch over large segments of the stellar mass range 5–15 $M_{\odot}$ when standard physical input parameters are adopted and (2) the delicate role potentially played by downward convective overshooting from the outer convection zone in determining whether a blue loop develops. This role was previously believed to be unimportant (Matraka, Wassermann, & Weigert 1982).

2. NEW EVOLUTIONARY SEQUENCES

Physical input parameters, such as thermodynamic state variables, opacities, and nuclear reaction rates, are adopted as in our previous work. Cox-Stewart opacities are used. To simplify the interpretation of the results, we have omitted mass loss, convective core overshooting, and both semiconvection and full convection in intermediate zones during all phases. In the outer convection zone, the ratio of convective mixing length to local pressure scale height is taken to be equal to unity. An initial hydrogen abundance by mass, $X_e = 0.739$, and an initial metals abundance by mass, $Z_e = 0.021$, are adopted. Masses of the stars are 3, 5, 7, 10, 15, and 30 $M_{\odot}$.

Evolutionary tracks running from the zero-age main sequence to nearly the end of core helium burning (specifically, $Y_c = 0.03$) are shown on the H-R diagram in Figure 1. Notice that the expected blue loops appear only for masses of 3 and 10 $M_{\odot}$, and not for 5, 7, 15, and 30 $M_{\odot}$. In our previous work where the convective mixing length was assumed to be 0.4 times the local density scale height, but the rest of the input physics was the same, blue loops arose for all masses studied, viz., 5, 7, 10, 15, and 30 $M_{\odot}$—although not for 30 $M_{\odot}$ when semiconvection was omitted (Stothers & Chin 1973, 1975; Carson & Stothers 1976). Whenever blue loops have occurred in other studies, the same regular pattern (up to some cutoff mass) has been obtained (e.g., Iben 1967; Paczýnski 1970a; Becker 1981; Bertelli, Bressan, & Chiosi 1985; Maeder & Meynet 1988; Castellani, Chieffi, & Straniero 1990).

It is clear that the present irregular pattern is highly unusual. A suspicion immediately arises that the models which remain red during core helium burning are only marginally stable

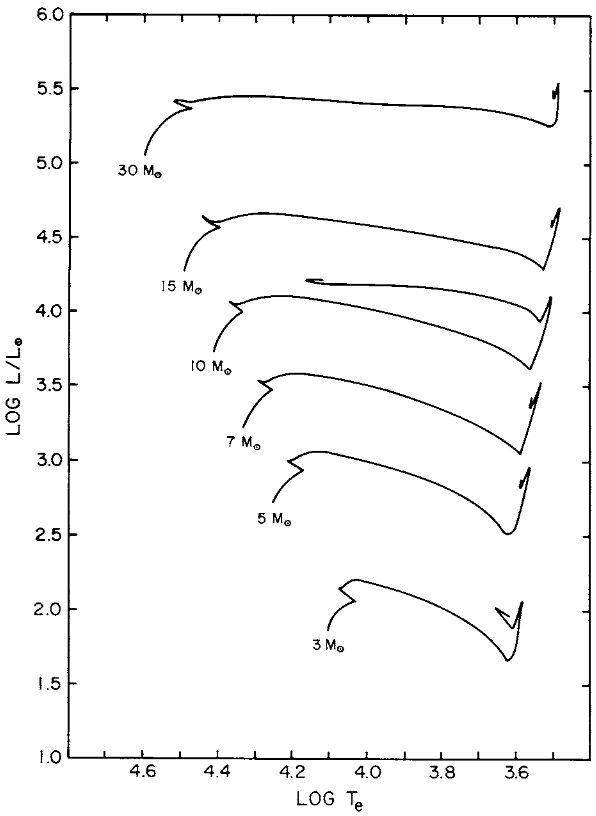

FIG. 1.—H-R diagram showing standard evolutionary tracks for all masses around the phase when a blue loop normally starts to develop.

Since a blue loop begins when the star's luminosity is lowest, convection in the outer envelope at this time is restricted to a relatively shallow zone near the surface (Iben 1967; Paczyński 1970b). Downward convective overshooting from such a shallow zone would have no effect on the star's hydrogen profile. However, at an earlier stage when the convective envelope reaches its greatest depth, downward overshooting would drive the hydrogen discontinuity deeper into the interior, thereby enhancing the possibility for a much closer approach of the hydrogen-burning shell to the hydrogen discontinuity before the end of core helium burning, as the shell burns its way outward.

Accordingly, we have arbitrarily lowered the inner boundary of the outer convection zone at this particular stage by a distance D and have then followed the subsequent evolution. We have found that convective overshooting beyond the formal convective envelope boundary indicated by Schwarzschild's criterion ($\nabla_{ad} = \nabla_{rad}$) does not need to penetrate very far in most cases to trigger a delayed blue loop when the star reaches its faintest luminosity. In units of the local pressure scale height the minimum required overshoot distance at the top of the red supergiant branch is $D/H_P = 0.3$, 0.3, and 0.4 for stars of 5, 7, and 15 $M_\odot$, respectively. Uncertainties of this general order in determining the true boundary of a deep stellar convection zone are by no means impossible (see Stothers & Chin 1990; Skaley & Stix 1991; and references therein). On the other hand, D/H_P must attain an unreasonably large value in excess of 1.5 to produce a blue loop at 30 $M_\odot$. The corresponding stellar mass fractions covered by convective overshooting are 0.014, 0.008, 0.002, and >0.002 in the four cases, respectively. The hydrogen profile for the star of 5 $M_\odot$ at the bottom of the red supergiant branch is shown in Figure 2.

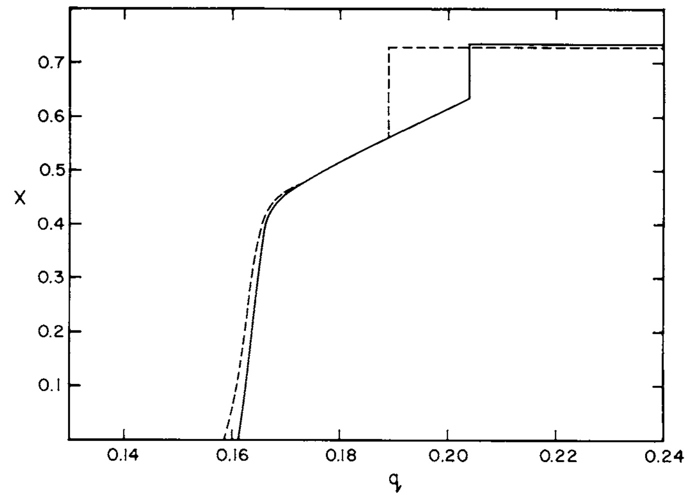

FIG. 2.—Hydrogen profile in a star of 5 $M_\odot$ when the star lies at the bottom of the red supergiant branch during core helium depletion. Profiles for standard evolution (*solid line*) and for marginally perturbed evolution (*dashed line*) are shown. The boundary of the zero-age main-sequence convective core occurs at a mass fraction $q = 0.230$.

Marginally perturbed evolutionary tracks for 5, 7, and 15 $M_\odot$ are presented in Figure 3, together with the unperturbed tracks for the three other masses. Applying the same amount of overshoot, $D/H_P = 0.3$, to the models for 3, 10, and 30 $M_\odot$ is

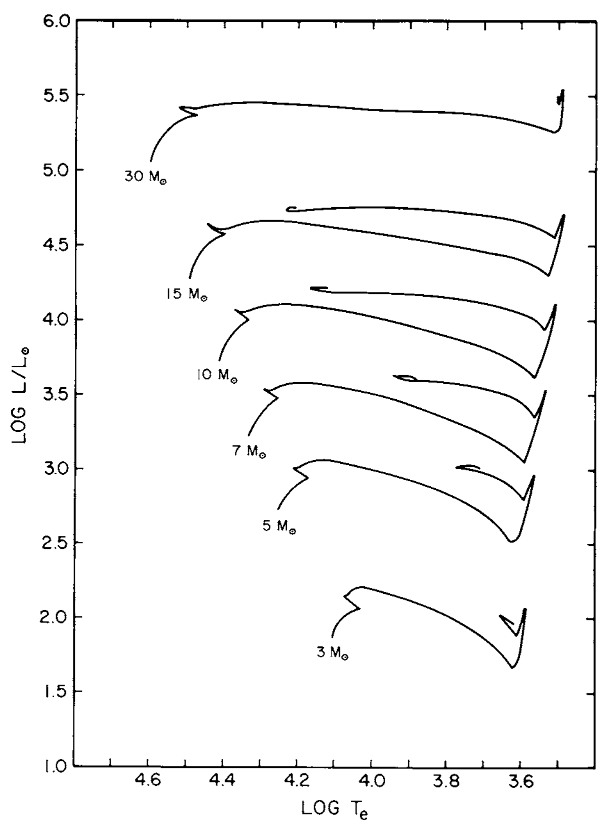

FIG. 3.—H-R diagram showing standard evolutionary tracks for 3, 10, and 30 $M_\odot$ and marginally perturbed evolutionary tracks for 5, 7, and 15 $M_\odot$. Compare this diagram with Fig. 1.

found to make very little difference for the evolutionary tracks at those masses. Matraka, Wassermann, & Weigert (1982) also found that the use of $D/H_P = 0.3$ made little difference to already formed blue loops. If D/H_P is increased further at the top of the red supergiant branch, the maximum extension of the blue loop simply becomes hotter (see also Alongi et al. 1991). This result is completely expected from previous studies of the effect of arbitrary alterations of the hydrogen profile on the star's evolutionary track (Stothers & Chin 1968; Robertson 1971; Lauterborn, Refsdal, & Weigert 1971; Fricke, Stobie, & Strittmatter 1971; Schlesinger 1977).

To confirm these conclusions, we recomputed the present evolutionary sequences with finer mass zoning and smaller time steps. Results proved to be essentially unchanged, thus ruling out numerical inaccuracies as a cause of the irregular pattern in Figure 1. We also used a much more extreme Population I initial chemical composition, $X_e = 0.650$ and $Z_e = 0.044$, and found that that the blue loop at 5 $M_\odot$ was still marginally suppressed. Therefore, the general state of marginal stability is not very sensitive to our original choice of initial chemical composition. Other tests indicate that inclusion of stellar wind mass loss tends to stabilize the red supergiant models, while convective core overshooting (if not too extensive) tends to destabilize them, promoting blue loops, except at the two highest stellar masses. Semiconvection and full convection in the intermediate zones during all phases of evolution also favor the occurrence of blue loops. Details of these results will be published elsewhere.

At all the masses above 3 $M_\odot$, the first few models along the blue loop evolved on the gravitational (Helmholtz-Kelvin) time scale of the envelope. At 3 $M_\odot$ itself, evolution everywhere along the loop occurred on the nuclear time scale of the core. The changeover mass for this alteration of time scale, however, is quite sensitive to the choice of input physics and may be as high as 8 $M_\odot$ (Lauterborn, Refsdal, & Roth 1971; Fricke & Strittmatter 1972; Gabriel and Noels 1974).

3. CONCLUSION

Blue loops on the H-R diagram during the core helium-burning phase have been the subject of many investigations, with attention being especially paid to their maximum extension and total duration. Far less attention has been focused on the question of their occurrence or nonoccurrence.

In addition to the fundamental physical input parameters for which astrophysically plausible departures from standard values are known to make the difference between a blue loop and no blue loop (see references in § 1), we are now able to include moderate downward convective overshooting from the outer convection zone. In the context of the present evolutionary tracks for stars of 5–15 $M_\odot$, overshoot distances of $D \approx 0.3$ H_P are sufficent to promote blue loops in those sequences that would otherwise not have them. These new results underscore how precarious a threshold phenomenon a blue loop really is.

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